

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property  
Organization  
International Bureau



(43) International Publication Date  
9 December 2004 (09.12.2004)

PCT

(10) International Publication Number  
**WO 2004/106582 A2**

(51) International Patent Classification<sup>7</sup>: C23C 14/14,  
14/08, 14/34, H01L 21/316

(21) International Application Number:  
PCT/US2004/014524

(22) International Filing Date: 21 May 2004 (21.05.2004)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:  
60/473,375 23 May 2003 (23.05.2003) US

(71) Applicant (for all designated States except US): SYM-  
MORPHIX, INC. [US/US]; 1278 Reamwood Avenue,  
Sunnyvale, CA 94089-2233 (US).

(72) Inventors; and

(75) Inventors/Applicants (for US only): DEMARAY,  
Richard, Ernest [US/US]; 190 Fawn Lane, Portola Valley,  
CA 94028 (US). ZHANG, Hongmei [US/US]; 1330 Rod-  
ney Drive, San Jose, CA 95118 (US). NARASIMHAN,  
Mukundan [IN/US]; 293 Bluefield Drive, San Jose, CA  
95136 (US). MILONOPOULOU, Vassiliki [GR/US];  
6160 Paseo Pueblo Drive, San Jose, CA 95120 (US).

(74) Agent: GARRETT, Arthur, S.; Finnegan, Henderson,  
Farabow, Garrett & Dunner, L.L.P., 1300 I Street N.W.,  
Washington, D.C. 20005-3315 (US).

(81) Designated States (unless otherwise indicated, for every  
kind of national protection available): AE, AG, AL, AM,  
AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN,  
CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI,  
GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE,  
KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD,  
MG, MK, MN, MW, MX, MZ, NA, NI, NO, NZ, OM, PG,  
PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SY, TJ, TM,  
TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM,  
ZW.

(84) Designated States (unless otherwise indicated, for every  
kind of regional protection available): ARIPO (BW, GH,  
GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM,  
ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM),  
European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI,  
FR, GB, GR, HU, IE, IT, LU, MC, NL, PL, PT, RO, SE, SI,  
SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ,  
GW, ML, MR, NE, SN, TD, TG).

**Published:**

— without international search report and to be republished  
upon receipt of that report

For two-letter codes and other abbreviations, refer to the "Guid-  
ance Notes on Codes and Abbreviations" appearing at the begin-  
ning of each regular issue of the PCT Gazette.

(54) Title: ENERGY CONVERSION AND STORAGE FILMS AND DEVICES BY PHYSICAL VAPOR DEPOSITION OF TI-  
TANIUM AND TITANIUM OXIDES AND SUB-OXIDES

(57) Abstract: High density oxide films are deposited by a pulsed-DC, biased reactive sputtering process from a titanium containing  
target to form high quality titanium containing oxide films. A method of forming a titanium based layer or film according to the  
present invention includes depositing a layer of titanium containing oxide by pulsed-DC, biased reactive sputtering process on a sub-  
strate. In some embodiments, the layer is TiO<sub>2</sub>. In some embodiments, the layer is a sub-oxide of Titanium. In some embodiments,  
the layer is Ti<sub>x</sub>O<sub>y</sub>, wherein x is between about 1 and about 4 and y is between about 1 and about 7. In some embodiments, the layer can  
be doped with one or more rare-earth ions. Such layers are useful in energy and charge storage, and energy conversion technologies.

WO 2004/106582 A2

BEST AVAILABLE COPY

## **Energy Conversion and Storage Films and Devices by Physical Vapor Deposition of Titanium and Titanium Oxides and sub-Oxides**

### **Related Applications**

The present invention claims priority to U.S. Provisional Application Serial No. 60/473,375, "Energy Conversion and Storage Devices by Physical Vapor Deposition of Titanium Oxides and Sub-Oxides," by Richard E. Demaray and Hong Mei Zhang, filed on May 23, 2003, herein incorporated by reference in its entirety.

### **Background**

#### **1. Field of the Invention**

[0001] The present invention is related to fabrication of thin films for planar energy and charge storage and energy conversion and, in particular, thin films deposited of titanium and titanium oxides, sub oxides, and rare earth doped titanium oxides and sub oxides for planar energy and charge storage and energy conversion.

#### **2. Discussion of Related Art**

[0002] Currently, titanium oxide layers are not utilized commercially in energy storage, charge storage, or energy conversion systems because such layers are difficult to deposit, difficult to etch, are known to have large concentrations of defects, and have poor insulation properties due to a propensity for oxygen deficiency and the diffusion of oxygen defects in the layers. Additionally, amorphous titania is difficult to deposit due to its low recrystallization temperature (about 250 °C), above which the deposited layer is often a mixture of crystalline anatase and rutile structures.

[0003] However, such amorphous titania layers, if they can be deposited in sufficient quality, have potential due to their high optical index,  $n \sim 2.7$ , and their high dielectric constant,  $k$  less than or equal to about 100. Further, they have substantial chemical stability. There are no known volatile halides and titania is uniquely resistant to mineral acids. Amorphous titania is thought to have the further advantage that there are no grain boundary mechanisms for electrical breakdown, chemical corrosion, or optical scattering. It is also well known that the sub oxides of titanium have unique and useful properties. *See, e.g.,* Hayfield, P.C.S., "Development of a

New Material- Monolithic  $\text{Ti}_4\text{O}_7$  Ebonix Ceramic", Royal Society Chemistry, ISBN 0-85405-984-3, 2002. Titanium monoxide, for example, is a conductor with a uniquely stable resistivity with varying temperature. Additionally,  $\text{Ti}_2\text{O}_3$ , which can be pinkish in color, is known to have semiconductor type properties. However, these materials have not found utilization because of their difficult manufacture in films and their susceptibility to oxidation. Further,  $\text{Ti}_4\text{O}_7$  demonstrates both useful electrical conductivity and unusual resistance to oxidation.  $\text{Ti}_4\text{O}_7$ , however, is also difficult to fabricate, especially in thin film form.

[0004] Additional to the difficulty of fabricating titanium oxide or sub oxide materials in useful thin film form, it also has proven difficult to dope these materials with, for example, rare earth ions, in useful or uniform concentration.

[0005] Therefore, utilization of titanium oxide and suboxide films, with or without rare earth doping, has been significantly limited by previously available thin film processes. If such films could be deposited, their usefulness in capacitor, battery, and energy conversion and storage technologies would provide for many value-added applications.

[0006] Current practice for construction of capacitor and resistor arrays and for thin film energy storage devices is to utilize a conductive substrate or to deposit the metal conductor or electrode, the resistor layer, and the dielectric capacitor films from various material systems. Such material systems for vacuum thin films, for example, include copper, aluminum, nickel, platinum, chrome, or gold depositions, as well as conductive oxides such as ITO, doped zinc oxide, or other conducting materials.

[0007] Materials such as chrome-silicon monoxide or tantalum nitride are known to provide resistive layers with 100 parts per million or less resistivity change per degree Centigrade for operation within typical operating parameters. A wide range of dielectric materials such as silica, silicon nitride, alumina, or tantalum pentoxide can be utilized for the capacitor layer. These materials typically have dielectric constants  $k$  of less than about twenty four (24). In contrast,  $\text{TiO}_2$  either in the pure rutile phase or in the pure amorphous state can demonstrate a dielectric constant as high as 100. See, e.g., R. B. van Dover, "Amorphous Lanthanide-Doped  $\text{TiO}_2$  Dielectric Films,"

Appl. Phys Lett., Vol. 74, no. 20, p. 3041-43 (May 17, 1999).

[0008] It is well known that the dielectric strength of a material decreases with increasing value of dielectric constant  $k$  for all dielectric films. A 'figure of merit' (FM) is therefore obtained by the product of the dielectric constant  $k$  and the dielectric strength measured in Volts per cm of dielectric thickness. Capacitive density of 10,000 to 12,000 pico Farads /mm<sup>2</sup> is very difficult to achieve with present conductors and dielectrics. Current practice for reactive deposition of titanium oxide has achieved a figure-of-merit, FM, of about 50 (k MV/cm). See J.-Y. Kim et al., "Frequency-Dependent Pulsed Direct Current Magnetron Sputtering of Titanium Oxide Films," J. Vac. Sci. Technol. A 19(2), Mar/Apr 2001.

[0009] Therefore, there is an ongoing need for titanium oxide and titanium sub-oxide layers, and rare-earth doped titanium oxide and titanium sub-oxide layers, for various applications.

#### Summary

[0010] In accordance with the present invention, high density oxide films are deposited by a pulsed-DC, biased, reactive sputtering process from a titanium containing target. A method of forming a titanium based layer or film according to the present invention includes depositing a layer of titanium containing oxide by pulsed-DC, biased reactive sputtering process on a substrate. In some embodiments, the layer is TiO<sub>2</sub>. In some embodiments, the layer is a sub-oxide of Titanium. In some embodiments, the layer is Ti<sub>x</sub>O<sub>y</sub> wherein  $x$  is between about 1 and about 4 and  $y$  is between about 1 and about 7.

[0011] In some embodiments of the invention, the figure of merit of the layer is greater than 50. In some embodiments of the invention, the layer can be deposited between conducting layers to form a capacitor. In some embodiments of the invention, the layer includes at least one rare-earth ion. In some embodiments of the invention, the at least one rare-earth ion includes erbium. In some embodiments of the invention, the erbium doped layer can be deposited between conducting layers to form a light-emitting device. In some embodiments of the invention, the erbium doped layer can be an optically active layer deposited on a light-emitting device. In some embodiments of the invention, the layer can be a protective layer. In some

embodiments, the protective layer can be a catalytic layer.

[0012] In some embodiments of the invention, the layer and a  $\text{TiO}_2$  layer can be deposited between conducting layers to form a capacitor with decreased roll-off characteristics with decreasing thickness of the  $\text{TiO}_2$  layer. In some embodiments, the  $\text{TiO}_2$  layer can be a layer deposited according to some embodiments of the present invention.

[0013] These and other embodiments of the present invention are further discussed below with reference to the following figures.

#### **Short Description of the Figures**

[0014] Figures 1A and 1B illustrate a pulsed-DC biased reactive ion deposition apparatus that can be utilized in the deposition according to the present invention.

[0015] Figure 2 shows an example of a target that can be utilized in the reactor illustrated in Figures 1A and 1B.

[0016] Figures 3A and 3B illustrate various configurations of layers according to embodiments of the present invention.

[0017] Figures 4A and 4B illustrate further various configurations of layers according to embodiments of the present invention.

[0018] Figure 5 shows another layer structure involving one or more layers according to the present invention.

[0019] Figure 6 shows a transistor gate with a  $\text{TiO}_y$  layer according to the present invention.

[0020] Figure 7 illustrates the roll-off of the dielectric constant with decreasing film thickness.

[0021] Figure 8 illustrates data points from a bottom electrode that helps reduce or eliminate the roll-off illustrated in Figure 7.

[0022] Figures 9A and 9B illustrate an SEM cross-section of a  $\text{Ti}_4\text{O}_7$  target obtained from Ebonex™ and an SEM cross section of the  $\text{Ti}_4\text{O}_{6.8}$  film deposited from the Ebonex™ target according to the present invention.

[0023] Figure 10 shows the industry standard of thin-film capacitor performance in comparison with layers according to some embodiments of the present invention.

[0024] Figure 11 shows the performance of various thin films deposited according

to the present invention in a capacitor structure.

[0025] Figure 12 shows a cross-section TEM and diffraction pattern amorphous and crystalline layers of  $\text{TiO}_2$  on  $n^{++}$  wafers.

[0026] Figure 13 shows a comparison of the leakage current for  $\text{TiO}_2$  films according to embodiments of the present invention with and without erbium ion doping.

[0027] Figures 14A and 14B show a photoluminescence signal measured from a 5000 Å layer of 10% erbium containing  $\text{TiO}_2$  deposited from a 10% erbium doped TiO conductive target and a photoluminescence signal measured from the same layer after a 30 minute 250 °C anneal.

[0028] In the figures, elements having the same designation have the same or similar functions.

#### Detailed Description

[0029] Miniaturization is driving the form factor of portable electronic components. Thin film dielectrics with high dielectric constants and breakdown strengths allow production of high density capacitor arrays for mobile communications devices and on-chip high-dielectric capacitors for advanced CMOS processes. Thick film dielectrics for high energy storage capacitors allow production of portable power devices.

[0030] Some embodiments of films deposited according to the present invention have a combination of high dielectric and high breakdown voltages. Newly developed electrode materials allow the production of very thin films with high capacitance density. The combination of high dielectric and high breakdown voltages produce thick films with new levels of available energy storage according to  $E=1/2CV^2$ .

[0031] Deposition of materials by pulsed-DC biased reactive ion deposition is described in U.S. Patent Application Serial No. 10/101863, entitled "Biased Pulse DC Reactive Sputtering of Oxide Films," to Hongmei Zhang, et al., filed on March 16, 2002. Preparation of targets is described in U.S. Patent Application Serial No. 10/101,341, entitled "Rare-Earth Pre-Alloyed PVD Targets for Dielectric Planar Applications," to Vassiliki Milonopoulou, et al., filed on March 16, 2002. U.S. Patent

Application Serial No. 10/101863 and U.S. Patent Application Serial No. 10/101,341 are each assigned to the same assignee as is the present disclosure and each is incorporated herein in their entirety. Additionally, deposition of materials is further described in U.S. Patent 6,506,289, which is also herein incorporated by reference in its entirety.

[0032] Figure 1A shows a schematic of a reactor apparatus 10 for sputtering of material from a target 12 according to the present invention. In some embodiments, apparatus 10 may, for example, be adapted from an AKT-1600 PVD (400 X 500 mm substrate size) system from Applied Komatsu or an AKT-4300 (600 X 720 mm substrate size) system from Applied Komatsu, Santa Clara, CA. The AKT-1600 reactor, for example, has three deposition chambers connected by a vacuum transport chamber. These AKT reactors can be modified such that pulsed DC (PDC) power is supplied to the target and RF power is supplied to the substrate during deposition of a material film. The PDC power supply 14 can be protected from RF bias power 18 by use of a filter 15 coupled between PDC power supply 14 and target 12.

[0033] Apparatus 10 includes a target 12 which is electrically coupled through a filter 15 to a pulsed DC power supply 14. In some embodiments, target 12 is a wide area sputter source target, which provides material to be deposited on substrate 16. Substrate 16 is positioned parallel to and opposite target 12. Target 12 functions as a cathode when power is applied to it and is equivalently termed a cathode. Application of power to target 12 creates a plasma 53. Substrate 16 is capacitively coupled to an electrode 17 through an insulator 54. Electrode 17 can be coupled to an RF power supply 18. Magnet 20 is scanned across the top of target 12.

[0034] For pulsed reactive dc magnetron sputtering, as performed by apparatus 10, the polarity of the power supplied to target 12 by power supply 14 oscillates between negative and positive potentials. During the positive period, the insulating layer on the surface of target 12 is discharged and arcing is prevented. To obtain arc free deposition, the pulsing frequency exceeds a critical frequency that depends on target material, cathode current and reverse time. High quality oxide films can be made using reactive pulsed DC magnetron sputtering in apparatus 10.

[0035] Pulsed DC power supply 14 can be any pulsed DC power supply, for example

an AE Pinnacle plus 10K by Advanced Energy, Inc. With this example supply, up to 10 kW of pulsed DC power can be supplied at a frequency of between 0 and 350 KHz. In some embodiments, the reverse voltage is 10% of the negative target voltage. Utilization of other power supplies will lead to different power characteristics, frequency characteristics, and reverse voltage percentages. The reverse time on this embodiment of power supply 14 can be adjusted to between 0 and 5  $\mu$ s.

[0036] Filter 15 prevents the bias power from power supply 18 from coupling into pulsed DC power supply 14. In some embodiments, power supply 18 can be a 2 MHz RF power supply, for example a Nova-25 power supply made by ENI, Colorado Springs, Co.

[0037] Therefore, filter 15 can be a 2 MHz band sinusoidal rejection filter. In some embodiments, the bandwidth of the filter can be approximately 100 kHz. Filter 15, therefore, prevents the 2 MHz power from the bias to substrate 16 from damaging power supply 18.

[0038] However, both RF sputtered and pulsed DC sputtered films are not fully dense and may typically have columnar structures. These columnar structures are detrimental to thin film applications. By applying a RF bias on wafer 16 during deposition, the deposited film can be densified by energetic ion bombardment and the columnar structure can be substantially eliminated or completely eliminated.

[0039] In the AKT-1600 based system, for example, target 12 can have an active size of about 675.70 X 582.48 by 4 mm in order to deposit films on substrate 16 that have dimension about 400 X 500 mm. The temperature of substrate 16 can be held at between -50C and 500C by introduction of back-side gas in a physical or electrostatic clamping of the substrate, thermo-electric cooling, electrical heating, or other methods of active temperature control. In Figure 1A, a temperature controller 22 is shown to control the temperature of substrate 16. The distance between target 12 and substrate 16 can be between about 3 and about 9 cm. Process gas can be inserted into the chamber of apparatus 10 at a rate up to about 200 sccm while the pressure in the chamber of apparatus 10 can be held at between about .7 and 6 millitorr. Magnet 20 provides a magnetic field of strength between about 400 and about 600 Gauss directed



in the plane of target 12 and is moved across target 12 at a rate of less than about 20-30 sec/scan. In some embodiments utilizing the AKT 1600 reactor, magnet 20 can be a race-track shaped magnet with dimension about 150 mm by 600 mm.

[0040] Figure 2 illustrates an example of target 12. A film deposited on a substrate positioned on carrier sheet 17 directly opposed to region 52 of target 12 has good thickness uniformity. Region 52 is the region shown in Figure 1B that is exposed to a uniform plasma condition. In some implementations, carrier 17 can be coextensive with region 52. Region 24 shown in Figure 2 indicates the area below which both physically and chemically uniform deposition can be achieved, where physical and chemical uniformity provide refractive index uniformity, for example. Figure 2 indicates that region 52 of target 12 that provides thickness uniformity is, in general, larger than region 24 of target 12 providing thickness and chemical uniformity. In optimized processes, however, regions 52 and 24 may be coextensive.

[0041] In some embodiments, magnet 20 extends beyond area 52 in one direction, the Y direction in Figure 2, so that scanning is necessary in only one direction, the X direction, to provide a time averaged uniform magnetic field. As shown in Figures 1A and 1B, magnet 20 can be scanned over the entire extent of target 12, which is larger than region 52 of uniform sputter erosion. Magnet 20 is moved in a plane parallel to the plane of target 12.

[0042] The combination of a uniform target 12 with a target area 52 larger than the area of substrate 16 can provide films of highly uniform thickness. Further, the material properties of the film deposited can be highly uniform. The conditions of sputtering at the surface of target 12, such as the uniformity of erosion, the average temperature of the plasma at the target surface and the equilibration of the target surface with the gas phase ambient of the process are uniform over a region which is greater than or equal to the region to be coated with a uniform film thickness. In addition, the region of uniform film thickness is greater than or equal to the region of the film which is to have highly uniform optical properties such as index of refraction, density, transmission, or absorptivity.

[0043] Target 12 can be formed of any materials, but is typically metallic materials such as, for example, combinations of In and Sn. Therefore, in some embodiments,

target 12 includes a metallic target material formed from intermetallic compounds of optical elements such as Si, Al, Er and Yb. Additionally, target 12 can be formed, for example, from materials such as La, Yt, Ag, Au, and Eu. To form optically active films on substrate 16, target 12 can include rare-earth ions. In some embodiments of target 12 with rare earth ions, the rare earth ions can be pre-alloyed with the metallic host components to form intermetallics. See U.S. Application Serial No. 10/101,341.

[0044] In several embodiments of the invention, material tiles are formed. These tiles can be mounted on a backing plate to form a target for apparatus 10. A wide area sputter cathode target can be formed from a close packed array of smaller tiles. Target 12, therefore, may include any number of tiles, for example between 2 to 20 individual tiles. Tiles are finished to a size so as to provide a margin of non-contact, tile to tile, less than about 0.010" to about 0.020" or less than half a millimeter so as to eliminate plasma processes that may occur between adjacent ones of the tiles. The distance between the tiles of target 12 and the dark space anode or ground shield 19 in Figure 1B can be somewhat larger so as to provide non contact assembly or provide for thermal expansion tolerance during processing, chamber conditioning, or operation.

[0045] As shown in Figure 1B, a uniform plasma condition can be created in the region between target 12 and substrate 16 in a region overlying substrate 16. A plasma 53 can be created in region 51, which extends under the entire target 12. A central region 52 of target 12, can experience a condition of uniform sputter erosion. As discussed further below, a layer deposited on a substrate placed anywhere below central region 52 can then be uniform in thickness and other properties (i.e., dielectric, optical index, or material concentrations). In addition, region 52 in which deposition provides uniformity of deposited film can be larger than the area in which the deposition provides a film with uniform physical or optical properties such as chemical composition or index of refraction. In some embodiments, target 12 is substantially planar in order to provide uniformity in the film deposited on substrate 16. In practice, planarity of target 12 can mean that all portions of the target surface in region 52 are within a few millimeters of a planar surface, and can be typically within 0.5 mm of a planar surface.

[0046] Figure 3A illustrates deposition of a layer 102 according to the present invention deposited on a substrate 101. In some embodiments, layer 102 can be a conducting protective layer of  $\text{TiO}_x$ . Figure 3B shows a first layer 102 according to the present invention deposited over a second layer 103, which can also be a layer according to some embodiments of the present invention. In some embodiments, first layer 102 can be a conducting protective layer and second layer 103 can be a titanium or other conducting layer. Layer 103 is deposited on substrate 101.

[0047] The fabrication of high density capacitor and resistor arrays as well as high energy storage solid state devices can be accomplished with embodiments of processes according to the present invention on a wide variety of substrates such as silicon wafers or glass or plastic sheets at low temperature and over wide area. With reference to Figure 3B, layer 102 can be an amorphous film of  $\text{TiO}_2$ , which is deposited by a process such as that described in U.S. Application Serial No. 10/101,341. Utilization or formation of a conducting layer 103 such as  $\text{TiO}$  or  $\text{Ti}_4\text{O}_7$  between a conducting layer of titanium, which is substrate 101, and the dielectric  $\text{TiO}_2$  layer 102 is shown in the present invention to substantially reduce or eliminate the 'roll off' of the dielectric constant  $k$  with decreasing film thickness below about 1000 Angstroms. Consequently, capacitors fabricated from titanium on low temperature substrates result in high value planar capacitors and capacitor arrays with very high capacitive density and low electrical leakage. Such electrical arrays are useful for shielding and filtering and buffering high frequency and may be used in stationary as well as in portable electronic devices.

[0048] In particular, the low temperature deposition of amorphous titania capacitors provides for the fabrication of integrated passive electronic circuits on plastic and glass. It also provides for the integration of such devices on other electronic devices and arrays at low temperature.

[0049] Similarly, a conducting layer of  $\text{TiO}$  or  $\text{Ti}_4\text{O}_7$  as layer 103 in Figure 3B, deposited between a conducting layer of titanium as layer 101 and a layer of titania as layer 102 of Figure 3B can be deposited so as to provide an increase in the surface smoothness by planarization of the titanium in layer 101 or other metallurgical conductive substrate layer 101 of Figure 3B. Consequently, roughness or asperity

based defects can be minimized or eliminated. As an example, charge injection from a metallurgical electrode can be decreased at the interface with a dielectric. The titanium based dielectric layer can be formed on a smooth conducting oxide layer, which according to some theories can prevent charge depletion of the high k dielectric layer, decrease point charge accumulation and support dipole formation at the conductor-dielectric interface, sometimes referred to as dipole coupling. These features are important to prevent the roll-off of the dielectric strength of the dielectric layer as the layer thickness is decreased below about 1000 Å. It is consequently useful in the formation of thin layers having high capacitive value.

[0050] A thick film of dielectric material may be deposited having a high dielectric strength for the storage of electrical energy. Such energy is well known to increase with the square of the applied Voltage. For example, in Figure 3B layer 102 can be a thick layer of dielectric according to the present invention. Layer 104 in Figure 3B, then, can be a conducting layer deposited on layer 102 while layer 103 is a conducting layer deposited between a substrate 101 and layer 102 to form a capacitor. As the dielectric strength of the amorphous dielectric layer of layer 102 increases in proportion to its thickness, the energy storage also increases effectively as the square of the thickness. It is shown that both record capacitance density and electrical energy storage density result for films according to the present invention. For thick film applications, smoothing of the metallurgical electrode by a conductive sub-oxide can decrease leakage at the interface in high voltage applications.

[0051] Protective conductive sub-oxide films of titanium can also be deposited on conductive and insulating substrates to protect them from harmful chemical attack while acting as conducting layers. For example, as illustrated in Figure 3A layer 102 can be a protective conductive sub-oxide film deposited on substrate 101. These layers can be used to protect an electrode, which can be substrate 101, from oxidation in the gas phase and in the liquid phase as well as the solid phase. Examples of such applications include electrolytic energy storage or as an active electrode surface for catalytic reactions and energy conversion such as in the oxygen-hydrogen fuel cell. Transparent oxides and semi-transparent sub-oxides can be deposited sequentially so that the conducting sub-oxides are protected by the transparent non-conducting oxides

for purposes of photovoltaic or electrochromic energy conversion devices. It is well known that organic based photovoltaic cells are enhanced by the presence of titania in the organic absorbing layer. Layers according to the present invention can be utilized both for the conductivity of electricity, the enhancement of the organic absorber, as well as the overall protection of the device.

[0052]  $\text{TiO}_2$  layers, for example, can photocatalytically produce ozone in the presence of sunlight. However, in the course of such activity, the  $\text{TiO}_2$  layer can build up a fixed charge. Absent a metallurgical conductor, as shown in Figure 3B layer 102 can be a catalytic oxide while layer 103 can be a conducting suboxide while substrate 101 is a dielectric substrate such as glass or plastic and layer 104 is absent. In such a two-layer device, where the oxide is provided on the surface of the sub-oxide, the sub-oxide can form an electrode so that electric charge can be conducted to the oxide layer for enhanced photochemical photolysis such as in an AC device, or for the purpose of charge dissipation.

[0053] Protective conductive sub-oxide films of titanium can also be deposited on conductive and insulating substrates to protect them from harmful chemical attack while acting as conducting layers for electrolytic energy storage or as an active electrode for catalytic energy conversion. Transparent and semi-transparent oxides can be deposited sequentially so that the conducting suboxides are protected by the transparent non-conducting oxide for purposes of protecting layered devices. Alternatively, it is well known that certain crystalline suboxides of titania, collectively referred to as Magnelli phases, possess unusual levels of durability to mineral acid solutions and other corrosive gaseous or liquid environments. Hayfield, P.C.S., "Development of a New Material- Monolithic  $\text{Ti}_4\text{O}_7$  Ebonix Ceramic", Royal Society Chemistry, ISBN 0-85405-984-3, 2002 describes these in detail and discusses many applications of the monolithic suboxides. Hayfield also explains that the basis of conductivity of sub-oxides is due to the presence of the  $\text{Ti}^{+2}$  cation in layers having the stoichiometry  $\text{TiO}$ . Of the several compositions,  $\text{Ti}_4\text{O}_7$  in particular is known to possess both useful conductivity and also chemical resistance to both anodization, which would decrease its conductivity, as well as reduction, which would decrease its chemical durability. Therefore, as shown in Figure 3A, substrate 101 can be a

metallurgical substrate such as aluminum or titanium and layer 102 can be  $\text{Ti}_4\text{O}_7$ . An example is the catalytic of  $\text{H}_2$  and  $\text{O}_2$  to make water and electricity.

[0054] In this disclosure, an amorphous coating layer according to embodiments of the present invention, derived from a crystalline target of  $\text{Ti}_4\text{O}_7$ , can obtain a similar composition as described above, measured as  $\text{Ti}_4\text{O}_{6.8}$ . Similar useful levels of chemical conductivity can be obtained. The sputtered film was dense, adherent, and also displayed robust durability to immersion in concentrated mineral acid and oxidizing solution. A similar material was deposited directly from a titanium target using the subject reactive sputtering process.

[0055] The increased density of the amorphous sputtered film according to embodiments of the present invention such as film 102 shown in Figure 3A can provide high levels of impermeability. Planarization can also be achieved by layer 102 over structures on substrate 101. Layer 102 can therefore achieve 'atomic' smooth surfaces on otherwise rough substrates. The sputtering process according to the present invention also allows the formation of a continuous range of stoichiometry between what are, in their crystalline environment, 'line compounds' with whole number integer ratios of titanium cations to oxygen atoms. In the present amorphous films, as long as one  $\text{Ti}^{+2}$  has a nearest neighbor cation in the amorphous glass matrix with the  $\text{Ti}^{+2}$  valence, conductive paths will be available in the sputtered film.

[0056] The sputtered sub-oxides also have the advantage that they can be layered, without removal from the vacuum system, with metallic titanium, other sub-oxides, as well as  $\text{TiO}_2$  for connection to electrical conduction and insulation. This feature provides the utility of multiplayer depositions by integrated processes in one vacuum chamber. Where thick films of a particular sub-oxide are desired, a target 12 (Figure 1) fabricated of the desired sub-oxide can be utilized.  $\text{TiO}$  is particularly a good conductor and possesses very stable resistivity with temperature variation.  $\text{Ti}_2\text{O}_3$  is a semiconductor. The higher oxygen-containing Magnelli compositions obtain higher resistivity as well as increased chemical stability and robustness and can be utilized as a resistive layer or as a protective, conductive layer.

[0057] Erbium doped  $\text{TiO}_2$  is known to display useful levels of

photoluminescence. And rare earth doped titanium oxide is known to display decreased levels of electrical leakage current under conditions of high electrical field. Layer 102 of Figure 3B, deposited according to some embodiments of the present invention, then can be erbium doped  $\text{TiO}_2$  and therefore displays very high level of breakdown and very low leakage under electrical stress. Additionally, a capacitor can be formed by deposition of conductors as layers 103 and 104 on a substrate 101. Consequently, capacitive and energy storage devices formed from rare earth doped layers formed according to the present invention are extremely useful for very high field applications such as capacitors, high voltage dielectric batteries, and electro luminescent devices and also for low-leakage devices.

[0058] A TiO or erbium-doped TiO target, target 12 of Figure 1A, can be formed by mixing of TiO powder or TiO powder and Erbium or Erbium-Oxide powder. TiO powder can be formed from the partial oxygenation in a controlled furnace. The mixed powder is then hipped under a controlled environment (for example hydrogen or  $\text{CO}_2$ ) to a high density to form tiles. As discussed above, such tiles can be mounted to form target 12. Additionally, other rare-earth doped titanium containing targets can be formed in the same fashion.

[0059] As an example, a layer of erbium doped titania or titania containing alloy deposited by means of the present invention, could be coupled as a continuous oxide layer to a photo diode constructed proximate to dielectric layer 102 of Figure 3A. Such an arrangement could provide an optical means for the measurement of the applied electrical field or the leakage current.

[0060] Alternatively, such a rare earth doped dielectric layer 102 might be coupled to conducting transparent oxides so that a light wave device might be provided for the conversion of electrical energy to light energy. In another embodiment, a titanium oxide containing a rare earth ion can be deposited directly on a light emitting diode device so that the rare earth ion can absorb some or all of the light emitted by the diode and re-fluoresce that light at another wavelength. In this embodiment, layer 102 can be a rare earth containing titanium oxide or sub oxide and substrate 101 includes a light emitting diode. An example of this may be the conversion of blue light from a LED to yellow-green light by layer 102. In that case,

layer 102 may be cerium doped titanium oxide or sub-oxide. Partial absorption of the blue light by layer 102 with conversion to yellow-green light by layer 102 would result in a white light source. Other colors of light can be obtained by doping the titanium oxide or sub-oxide with other rare earth ions.

**[0061]** Figures 4A and 4B illustrate further stackings of layers according to embodiments of the present invention. For example, layer 201 can be a  $\text{TiO}_2$  dielectric protective deposited over a conducting layer 103 on substrate 101. Figure 4B can show dielectric protective layer 201 deposited over conducting protective layer 102 of  $\text{TiO}_y$ , which is deposited on a metal conducting layer 103 on substrate 101. The  $\text{TiO}_y$  conducting protective layer can act as a smoothing layer, resulting in a better barrier layer in dielectric 201. The end result is a better roll-off characteristic than has previously been obtained.

**[0062]** In general, layer 102 can be formed of any  $\text{Ti}_x\text{O}_y$  layer or rare earth doped  $\text{Ti}_x\text{O}_y$  layer according to the present invention. As illustrated here, layers of various compositions of  $\text{Ti}_x\text{O}_y$ , with or without rare-earth doping, have various properties. In some embodiments of the invention, x can be between about 1 and about 4 and y can be between about 1 and about 7.

**[0063]** Figure 5 shows an example of a capacitor stack according to the present invention. A metal conducting layer 103 is deposited on substrate 101. A conducting protective layer 102 is deposited over conducting layer 103 and a  $\text{TiO}_2$  dielectric protective layer is deposited over the protective conducting layer 102. Another protective conducting layer 102 can be deposited over the  $\text{TiO}_2$  dielectric layer and a metal layer can be deposited over the protective conducting layer 102. The resulting capacitor stack has upper and lower smoothing due to the two  $\text{TiO}_y$  layers and results in improved roll-off characteristics in the dielectric constant. Such capacitor stacks can be very useful in energy storage devices.

**[0064]** Figure 6 shows a transistor structure according to the present invention. A source 401, drain 402 and gate structure 404 are deposited on a semiconducting substrate 403. An intermediate dielectric 400 can then be deposited over the source, drain and gate structure. A protective conducting layer 102, which can be formed of  $\text{TiO}_y$ , can then be deposited over an opening in the intermediate dielectric layer 400



followed by a conducting layer 103. The protective conducting layer 102 prevents roll-off of the gate dielectric 404.

Example 1. Deposition of  $\text{Ti}_4\text{O}_7$  film

[0065] In this example,  $\text{Ti}_4\text{O}_7$  films were deposited using a Pulse DC scanning magnetron PVD process as was previously described in U.S. Application Serial No. 10/101,341. The target was a about 1mm thick, about  $16.5 \times 12.5 \text{ mm}^2$  tiles of titanium oxide target obtained from a sheet of Ebonex™ which compounded of bulk  $\text{Ti}_4\text{O}_7$  was bonded onto a backing plate. Ebonex™ can be obtained from Atraverda Ltd., Oakham Business Park, Mansfield, UK. A pulsed DC generator from Advanced Energy (Pinnacle Plus) was used as the target power supply. The pulsing frequency can be varied from 0-350 KHz. Reversed duty cycle can be varied from  $1.3\mu\text{s}$  to  $5\mu\text{s}$  depending on the pulsing frequency. Target power was fixed at 2 KW and pulsing frequency was 200KHz during deposition, Ar flow rate is 100sccm. The deposition rate at this condition is  $14\text{\AA}/\text{sec}$  over a 40 by 50 cm substrate 101. A 100 W at 2 MHz bias was supplied to the substrate. The bias power supply can be an RF supply produced by ENI.

[0066] Utilizing the above parameters, a layer 102 of Figure 3A was deposited on a substrate 101 of 150mm p-type Si wafer. The sheet resistance was measured using 4 point probe to be 140 ohms/sq, with film thickness of  $1.68\mu\text{m}$ . The resistivity of the resulting film is measured to be 0.023 ohms-cm. The composition of film was determined using EDX to be  $\text{Ti}_4\text{O}_{6.8}$ .

Example 2. Deposition of  $\text{TiO}_2$  on Ti- $\text{Ti}_4\text{O}_7$  film Stack

[0067] In this example,  $\text{TiO}_2$  films were deposited using a 2MHz RF biased, Pulse DC scanning magnetron PVD process as was previously described in U.S. Application Serial No. 10/101,341. The substrate size can be up to  $600 \times 720 \text{ mm}^2$ . The target was a ~7mm thick,  $\sim 630 \times 750 \text{ mm}^2$  Ti plate of 99.9% purity. A pulsed DC generator, or PDC power supply from Advanced Energy (Pinnacle Plus) was used as the target power supply. The pulsing frequency can be varied from 0-350 KHz. Reversed duty cycle can be varied from  $1.3\mu\text{s}$  to  $5\mu\text{s}$  depending on the pulsing

frequency. An ENI RF generator and ENI Impedance matching unit were used for the substrate bias. A 100 W with a 2 MHz RF generator, which can be an EFI supply, was utilized. The chamber base pressure was kept below  $2 \times 10^{-7}$  Torr. The substrate temperature was below 200°C during deposition.

[0068] A systematic DOE (design of experiments) were carried out on both n++ type bare Si wafers and Al metallized wafers. All n++ wafers were HF cleaned just before loading into the chamber for deposition. A series of 150nm thick, Al films were deposited onto the bare Si wafers using the same PVD system at low temperature (<100°C).

[0069] The total PDC target power, pulsing frequency, oxygen partial pressure, and substrate bias power were variables in the DOE. Total gas flow of Ar and O<sub>2</sub> were kept constant at 100 sccm. The PDC target power was between 4 and 7 kW with a pulsing frequency of between 100 and 250 kHz. The oxygen flow rate ranged from 30 to 60%. The bias power ranged from 0 to 300 W at 2 Mhz. Both dielectric strength and breakdown voltage were measured using a mercury probe. Film thickness in this DOE range from 100nm to 270nm.

[0070] Therefore, with reference to Figure 3B, layer 101 is the Si wafer substrate, layer 103 is the 150 nm thick Al layer, layer 102 is the Ti<sub>4</sub>O<sub>7</sub> layer, and layer 104 is TiO<sub>2</sub>. Figure 7 shows the thickness dependence of the dielectric constant of layer 102, showing the roll off effect. The capacitance of the layer stack 101, 103, 102, and 104 was measured with a mercury electrode impressed upon layer 104 and coupled to layer 103. The precise thickness of dielectric layer 104 was measured optically. The dielectric constant of layer 104 was then calculated from the measured capacitance. As shown in Figure 7, the TiO<sub>2</sub> film thickness decreases, so does the dielectric constant of the TiO<sub>2</sub> film.

[0071] However, this roll-off effect can be greatly reduced or eliminated in certain embodiments of the present invention. Figure 8 shows two additional data points shown as circles which represent the dielectric constant of thin TiO<sub>2</sub> layers for layer 104 with Ti-Ti<sub>4</sub>O<sub>7</sub> deposited as layer 102 of Figure 3B.

Example 3. Deposition of  $\text{TiO}_2$  on  $\text{Ti-TiO}_x$  ( $x < 2$ ) film Stack

[0072] A layer of  $\text{TiO}_2$  was deposited on a titanium coated substrate. About 2000 Å of Ti metal was deposited at 7KW of PDC target power, with Ar flow of 100 sccm and bias power of 200W. After Ti deposition,  $\text{TiO}_2$  was deposited in the same chamber without oxide burn in. This process resulted in a  $\text{Ti-TiO}_y\text{-TiO}_2$  ( $y < 2$ ) film stack. The k value of a 200Å film was as high as 60.

[0073] Figures 9A and 9B illustrate an SEM cross-section of a  $\text{Ti}_4\text{O}_7$  Ebonex™ target (Figure 9A) and an SEM cross section of the  $\text{Ti}_4\text{O}_{6.8}$  layer (Figure 9B) deposited from the Ebonex™ target according to the present invention. The deposited film shows smooth deposition of the layer. The Ebonex™ target shown in Figure 9A shows an open porosity material with high roughness. The deposited layer shown in Figure 9B, however, shows a highly dense layer with a smooth surface condition.

[0074] Table I shows the effects of the dielectric properties of  $\text{TiO}_2$  deposited according the present invention in comparison with previously obtained values. The values for the previously obtained reactive sputtering was taken from the paper "Frequency-Dependent Pulsed Direct Current magnetron Sputtering of Titanium Oxide Films," by J. Y. Kim et al., J. Vac. Sci. Techn., A 19(2), Mar/Apr. 2001. The values for PDC PVD with bias was experimentally obtained from layers deposited as described in Example 2 above.

Table I

Process	$V_{bd}$ (Mv/cm)	K	FM
Reactive Sputtering	0.46 ~ 1.35	34 ~ 65.9	19 ~ 50
PDC physical Vapor Deposition with Bias	3.48	83	288

[0075] As can be seen from Table I, the breakdown voltage  $V_{bd}$  is significantly improved in layers according to the present invention. Further, the dielectric constant of the resulting layer is also higher. The figure of merit (FM) then for the deposited

layer was 288, very much higher than that report by Kim et al. The reference Kim et al. was the reference reporting the best quality  $\text{TiO}_2$  films available at the time of filing of the prior application to which this disclosure claims priority.

[0076] Figure 10 shows data of capacitance made with layers according to the present invention in processes as described in Example 2 above are shown in comparison with available industry values. As is observed in Figure 10, layers of  $\text{TiO}_2$  deposited according to the present invention have higher dielectric breakdown voltages than other dielectric films utilized in industry, which is represented by the solid line. However, due to the roll-off in dielectric constant  $K$  in films below about 1000 Å in thickness (as is indicated in the top two points in Figure 10), a capacitance density above about 5000 or 6000 pF/mm<sup>2</sup> could not be achieved using thinner films. This is also shown in Figure 7.

[0077] However, combined with the use of a conductive sub-oxide and the higher dielectric constant of thinner films as shown in Figure 11, a capacitance density of 12000 pF/mm<sup>2</sup> can be achieved with a 500 Å thickness film and a capacitance density of greater than 24000 pF/mm<sup>2</sup> can be achieved with a 220 Å film, as is shown in Figure 11. These film stacks were deposited as described in Example 3 above.

[0078] Figure 12 shows a deposited layer 102 on a substrate 101 formed of n++ silicon wafer. Layer 102 is formed of  $\text{TiO}_2$  deposited according to the present invention. As shown in the SEM cross-section, the  $\text{TiO}_2$  layer shows several layers. A layer 1201 is formed of  $\text{SiO}_2$  formed on substrate 101 and is formed about 20 Å thick. An amorphous layer 1202 of thickness about 250 Å is then formed above layer 1201. Finally, a crystalline  $\text{TiO}_2$  layer 1203 is formed about 4000 Å thick. In some embodiments of the present invention, a continuous deposition on a substrate results in a first amorphous layer deposited at initially cooler temperature followed by a further crystalline layer deposited during the increased temperature of the process. A diffraction pattern inset in Figure 12 illustrates the crystalline nature of layer 1203.

[0079] Table II tabulates data taken from a number of bi-layer film such as that shown in Figure 12 and completely amorphous films formed by repeated initial deposition layers at cool deposition conditions. Films near 1000 Å of thickness are compared and display similar values for the dielectric constant. However, the

amorphous film exhibits much higher dielectric breakdown strengths. Due to the similar thickness and values of the dielectric constant, the two films exhibit similar values for capacitance. However, the amorphous film illustrates superior breakdown voltage and therefore has a higher figure of merit (FM). These trends are more pronounced in the thicker films with thicknesses close to 2000 Å. In this case, the values of the dielectric constant and capacitance are nearly identical but again there is a significantly higher breakdown voltage in the amorphous film, which results in a significant improvement in the figure of merit for the amorphous films.

Table II

Film Thickness (nm)	k	V <sub>bd</sub> (MV/cm)	FM	C (pF/mm <sup>2</sup> )	Breakdown Voltage (V)	Film Morphology
969	63	3.6	227	540	348	Bi-layer
1036	62	6.4	396	538	660	Amorphous
2020	98	3.5	335	429	705	Bi-Layer
2322	98	5.5	539	429	1110	Amorphous

[0080] Therefore, it is clear that amorphous TiO<sub>2</sub> films have much better performance. As discussed above, those layers are the result of low temperature depositions. Therefore, as was demonstrated with the data shown in Table II, one method of producing thick amorphous TiO<sub>2</sub> layers is to simply utilize a sequence of low temperature depositions, halting the deposition prior to thermal heating of the depositing film. However, this method can take a significant amount of production time for thick films. Another embodiment of obtaining thick TiO<sub>2</sub> amorphous films is to apply active cooling to the substrate in an amount sufficient to provide continuously amorphous TiO<sub>2</sub> films.

[0081] Figure 13 shows a comparison of the leakage current for TiO<sub>2</sub> films according to embodiments of the present invention with and without erbium ion doping. The lower data points in Figure 13 are from capacitors formed from films deposited from a 10 at. % Er doped TiO target. The target was electrically

conductive. One example of the 10% doped film of 1000 Å thickness was formed with 60 sccm Ar, 6 sccm O<sub>2</sub>, with a target power of 3 kW, bias power of 100 W, with a deposition time of 200 sec on a metal coated glass wafer. With the metal coating forming a copper titanium lower electrode and a titanium copper gold upper electrode patterned as 1X1 mm, discrete capacitors was then formed. The layers corresponding to the upper data points were deposited from a pure titanium target with no erbium doping on a TaN substrate with a evaporated platinum upper electrode. This structure of the bottom data is illustrated in Figure 4B where, for example, layer 101 is a glass substrate, layer 103 is a copper titanium layer, layer 102 is the erbium doped TiO<sub>2</sub> layer, and layer 201 is a titanium copper gold layer.

[0082] As can be seen in Figure 13, the leakage current density is reduced by many orders of magnitude by addition of erbium.

[0083] Figures 14A and 14B show a photoluminescence signal with excitation at 580 nm and measurement at 1.53 μm, measured from a 5000 Å layer of 10% erbium containing TiO<sub>2</sub> deposited from a 10% erbium doped TiO conductive target and a photoluminescence signal measured from the same layer after a 30 minute 250 °C anneal, respectively. Table III shows similar data for several layers deposited from the erbium-doped TiO conductive target.

Table III

Thickness	Before Anneal	Anneal (°C)	After Anneal
5000 Å	6704	150	5809
5000 Å	6493	200	4042
5000 Å	6669	250	2736
5000 Å	6493	300	3983
1 μm	6884	150	6743
1 μm	5197	200	3685
1 μm	6253	250	3612
1 μm	5324	300	3381

[0084] According to some explanations of the reduction of leakage current in layers as illustrated by Figure 13, fast electrons that have sufficient energy to excite

the erbium ion would cause the rare earth ion to undergo excitation upon electron impact or passage within a distance sufficient for energy exchange. Consequently, the leakage current electrons capable of causing ionization within the dielectric oxide would be reduced by electron collisions with erbium ions. Excited state ions have at least two relaxation mechanisms for disposal of the energy: radiative and non-radiative. In radiative relaxation, the excited ion emits light. In non-radiative relaxation, the excited ion undergoes a cooperative process with vibrational modes of its host dielectric oxide and produces a vibration which is the elemental form of heat. In the data illustrated in Figure 13, it was not possible to observe light in the leakage test, but photoluminescence was observed from optical excitation of the similar 10% Er doped TiO<sub>2</sub> deposited from the 10% Er doped TiO conductive target, as shown in Table III.

[0085] As can be seen from the data in Table III, an erbium doped layer of titanium oxide was shown to fluoresce strongly under optical excitation by light of a wavelength 580 nm, using a Phillips PhotoLuminescence Microscope, model no. PLM-100. The target was electrically conductive and sputtered at a higher rate and a lower oxygen partial pressure than characteristic of a metallic titanium target. One example of the 10% doped film of 2,032 angstroms was 60 sccm Ar, 6 sccm O<sub>2</sub>, with a target power of 3 kW, bias power of 100 W, with a deposition time of 300 sec.

[0086] The level of photoluminescence observed from the layer was similar to that obtained in as-deposited and annealed films providing commercial levels of optical absorption and fluorescence for applications to planar waveguide amplifiers having at least 15 dB gain for signals as weak as -40dB at the 1.5 micron wavelength utilized for photonic C band communications.

[0087] Such a device can be illustrated with Figure 3B, where layer 103 can be a conductive layer deposited on substrate 101, layer 102 can be a rare-earth doped TiO<sub>2</sub> layer deposited according to embodiments of the present invention, and layer 104 can be a further conductive layer or a conductive transparent layer to form an metal-insulating-metal (MIM) capacitor structure. Such a structure could function as a light emitting layer under either DC or AC electrical excitation. In another embodiment, layer 103 can be a lift-off layer such as CaF<sub>2</sub> or other organic material, layer 102 is

the rare-earth doped  $\text{TiO}_2$  layer, and layer 104 is absent, then upon lift-off or upon transfer of layer 102, a free standing or applied layer having electroluminescent or photoluminescent applications can be provided over a selected device.

[0088] Thin films according to the present invention can be utilized in advanced display devices, electrical energy storage and conversion, and to form optical and electronic films with scratch resistance and barrier properties. Advanced display product applications include OLED encapsulation, barriers for flexible polymer substrates, outcoupling mirrors and anti-reflection coatings, transparent conducting oxides, and semiconducting materials for active matrix displays. Electrical energy storage and conversion applications include high density capacitor arrays for mobile communication devices, on-chip high "K" capacitors for advanced CMOS, and high voltage energy storage for portable power devices. Other applications include touch-sensitive devices and durable bar code scanners and see-through sensors as well as implantable biometric devices.

[0089] The embodiments described in this disclosure are examples only and are not intended to be limiting. Further, the present invention is not intended to be limited by any particular theory or explanation presented to explain experimental results. As such, examples of titanium oxide and titanium sub-oxide films illustrated herein and their applications are not intended to be limiting. One skilled in the art may contemplate further applications or films that are intended to be within the spirit and scope of the present invention. As such, the invention is limited only by the following claims.



### Claims

We claim:

1. A method of forming a titanium based layer, comprising:  
depositing a layer of titanium containing oxide by pulsed-DC, biased reactive sputtering process on a substrate.
2. The method of claim 1, wherein the layer is  $\text{TiO}_2$ .
3. The method of claim 2, wherein the figure of merit of the layer is greater than 50.
4. The method of claim 2, wherein the layer is deposited between conducting layers to form a capacitor.
5. The method of claim 2, wherein the layer includes at least one rare-earth ion.
6. The method of claim 5, wherein the layer is deposited between conducting layers to form a capacitor.
7. The method of claim 5, wherein the at least one rare-earth ion includes erbium.
8. The method of claim 5, wherein the layer is deposited between conducting layers to form a light-emitting device.
9. The method of claim 5, wherein the layer is an optically active layer deposited on a light-emitting device.
10. The method of claim 5, wherein the layer is an optically active layer applied to a light-emitting device.
11. The method of claim 1, wherein the layer is a sub-oxide of Titanium.
12. The method of claim 11, wherein the figure of merit of the layer is greater than 50.
13. The method of claim 11, wherein the layer is deposited between conducting layers to form a capacitor.
14. The method of claim 11, wherein the layer includes at least one rare-earth ion.
15. The method of claim 14, wherein the layer is deposited between conducting layers to form a capacitor.
16. The method of claim 14, wherein the at least one rare-earth ion includes erbium.
17. The method of claim 14, wherein the layer is deposited between conducting layers to form a light-emitting device.

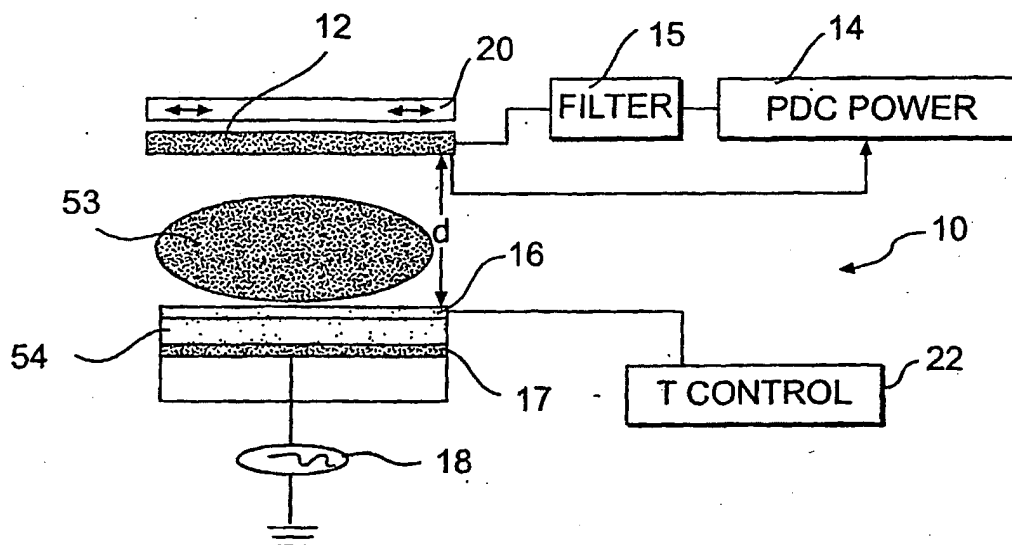
18. The method of claim 14, wherein the layer is an optically active layer deposited on a light-emitting device.
19. The method of claim 14, wherein the layer is an optically active layer applied to a light-emitting device.
20. The method of claim 2, wherein the layer is a protective layer.
21. The method of claim 20, wherein the protective layer is a catalytic layer.
22. The method of claim 20, wherein the protective layer includes at least one rare-earth ion.
23. The method of claim 1, wherein the layer is  $Ti_xO_y$  wherein x is between about 1 and about 4 and y is between about 1 and about 7.
24. The method of claim 23, wherein the figure of merit of the layer is greater than 50.
25. The method of claim 23, further including depositing an  $TiO_2$  layer on the layer wherein the layer and the  $TiO_2$  layers are deposited between conducting layers to form a capacitor with decreased roll-off characteristics with decreasing thickness of the  $TiO_2$  layer.
26. The method of claim 23, wherein the  $TiO_2$  layer is an amorphous layer deposited by a pulsed DC, biased, reactive ion process.
27. The method of claim 23, wherein the layer includes at least one rare-earth ion.
28. The method of claim 27, wherein the at least one rare-earth ion includes erbium.
29. The method of claim 27, wherein the layer is deposited between conducting layers to form a light-emitting device.
30. The method of claim 27, wherein the layer is an optically active layer deposited on a light-emitting device.
31. The method of claim 27, wherein the layer is an optically active layer applied to a light-emitting device.
32. The method of claim 23, wherein the layer is a conducting oxide.
33. The method of claim 32, wherein the substrate is a conducting electrode and the layer is a protective layer.
34. The method of claim 33, wherein the protective layer is a catalytic layer.

35. The method of claim 33, wherein the protective layer includes at least one rare-earth ion.
36. The method of claim 32, wherein the substrate is a dielectric and the layer is a protective layer.
37. The method of claim 36, wherein the protective layer is a catalytic layer.
38. The method of claim 1, further including  
controlling the temperature of the substrate during deposition.
39. The method of claim 38, wherein controlling the temperature includes active temperature control.
40. The method of claim 1, wherein the layer is an amorphous layer.
41. The method of claim 1, wherein the substrate includes a transistor structure.
42. A titanium based layer, comprising:  
a layer compounded from titanium and oxygen deposited by pulsed-DC, biased reactive sputtering process on a substrate.
43. The layer of claim 42, wherein the layer is  $\text{TiO}_2$ .
44. The layer of claim 43, wherein the figure of merit of the layer is greater than 50.
45. The layer of claim 43, wherein the layer is deposited between conducting layers to form a capacitor.
46. The layer of claim 43, wherein the layer includes at least one rare-earth ion.
47. The layer of claim 46, wherein the layer is deposited between conducting layers to form a capacitor.
48. The layer of claim 46, wherein the at least one rare-earth ion includes erbium.
49. The layer of claim 46, wherein the layer is deposited between conducting layers to form a light-emitting device.
50. The layer of claim 46, wherein the layer is an optically active layer deposited on a light-emitting device.
51. The layer of claim 46, wherein the layer is an optically active layer applied to a light-emitting device.
52. The layer of claim 42, wherein the layer is sub-oxide of Titanium.
53. The layer of claim 52, wherein the figure of merit is greater than 50.

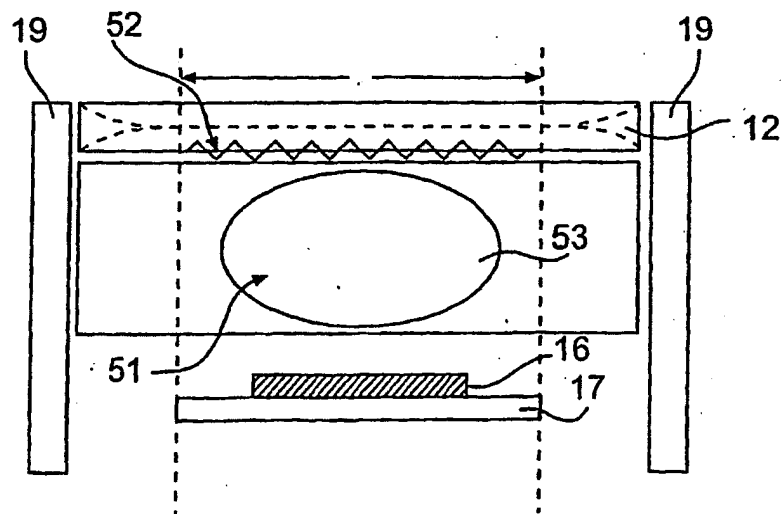
54. The layer of claim 52, wherein the layer is deposited between conducting layers to form a capacitor.
55. The layer of claim 52, wherein the layer includes at least one rare-earth ion.
56. The layer of claim 55, wherein the layer is deposited between conducting layers to form a capacitor.
57. The layer of claim 55, wherein the at least one rare-earth ion includes erbium.
58. The layer of claim 55, wherein the layer is deposited between conducting layers to form a light-emitting device.
59. The layer of claim 55, wherein the layer is an optically active layer deposited on a light-emitting device.
60. The layer of claim 55, wherein the layer is an optically active layer applied to a light-emitting device.
61. The layer of claim 43, wherein the layer is a protective layer.
62. The layer of claim 61, wherein the protective layer is a catalytic layer.
63. The layer of claim 61, wherein the protective layer includes at least one rare-earth ion.
64. The layer of claim 42, wherein the layer is  $\text{Ti}_x\text{O}_y$  wherein  $x$  is between about 1 and about 4 and  $y$  is between about 1 and about 7.
65. The layer of claim 64, wherein the figure of merit is greater than 50.
66. The layer of claim 64, further including depositing an  $\text{TiO}_2$  layer on the layer wherein the layer and the  $\text{TiO}_2$  layers are deposited between conducting layers to form a capacitor with decreased roll-off characteristics with decreasing thickness of the  $\text{TiO}_2$  layer.
67. The layer of claim 64, wherein the  $\text{TiO}_2$  layer is an amorphous layer deposited by a pulsed DC, biased, reactive ion process.
68. The layer of claim 64, wherein the layer includes at least one rare-earth ion.
69. The layer of claim 68, wherein the at least one rare-earth ion includes erbium.
70. The layer of claim 68, wherein the layer is deposited between conducting layers to form a light-emitting device.
71. The layer of claim 68, wherein the layer is an optically active layer deposited on a light-emitting device.

72. The layer of claim 68, wherein the layer is an optically active layer applied to a light-emitting device.
73. The layer of claim 64, wherein the layer is a conducting oxide.
74. The layer of claim 73, wherein the substrate is a conducting electrode and the layer is a protective layer.
75. The layer of claim 74, wherein the protective layer is a catalytic layer.
76. The layer of claim 74, wherein the protective layer includes at least one rare-earth ion.
77. The layer of claim 73, wherein the substrate is a dielectric and the layer is a protective layer.
78. The layer of claim 77, wherein the protective layer is a catalytic layer.
79. The layer of claim 42, further including  
controlling the temperature of the substrate during deposition.
80. The layer of claim 79, wherein controlling the temperature includes active temperature control.
81. The layer of claim 42, wherein the substrate includes a transistor structure.
82. The layer of claim 42, wherein the layer is an amorphous layer.
83. A target, comprising:  
hipped TiO having composition TiO.
84. The target of claim 83, further including at least one rare-earth dopant.
85. A method of forming a target, comprising:  
forming a TiO powder;  
mixing the TiO powder to form a mix;  
hipping the mix under a controlled atmosphere to form tiles; and  
forming a target from the tiles.
86. The method of claim 85, further including mixing at least one rare-earth oxide powder with the mix.
87. The method of claim 86, wherein the at least one rare-earth oxide includes erbium oxide.

1/15

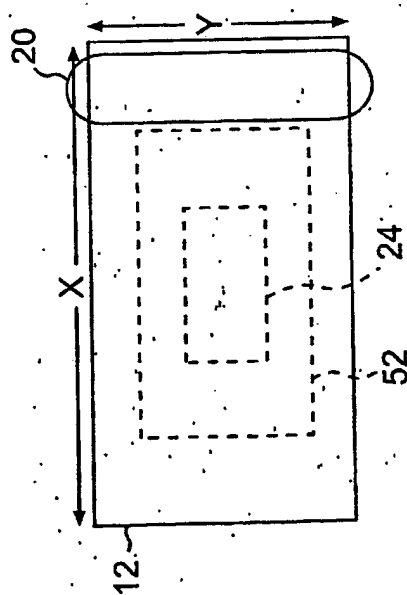


**FIG. 1A**



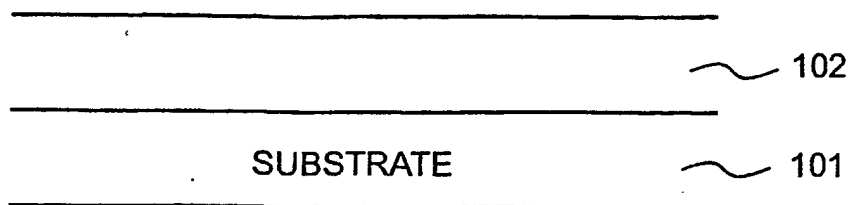
**FIG. 1B**

2/15

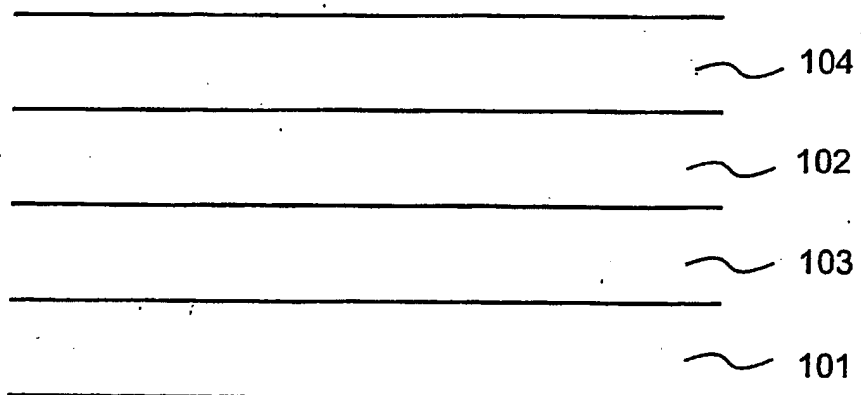


**FIG. 2**

3/15



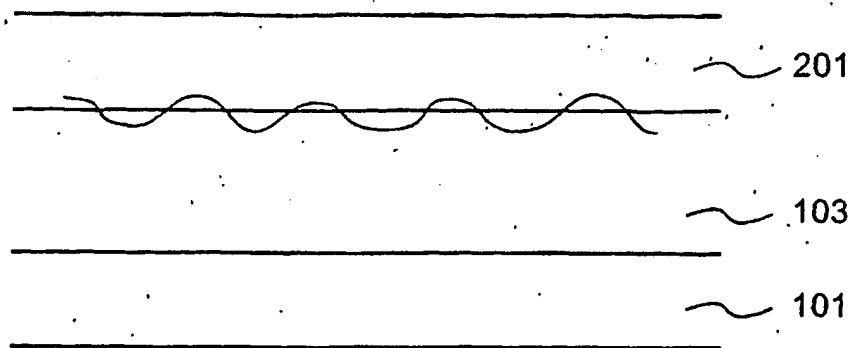
**FIG. 3A**



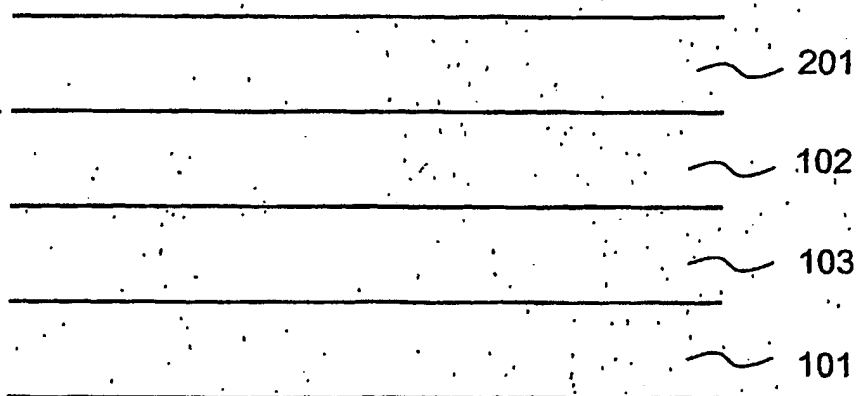
**FIG. 3B**



4/15



**FIG. 4A**



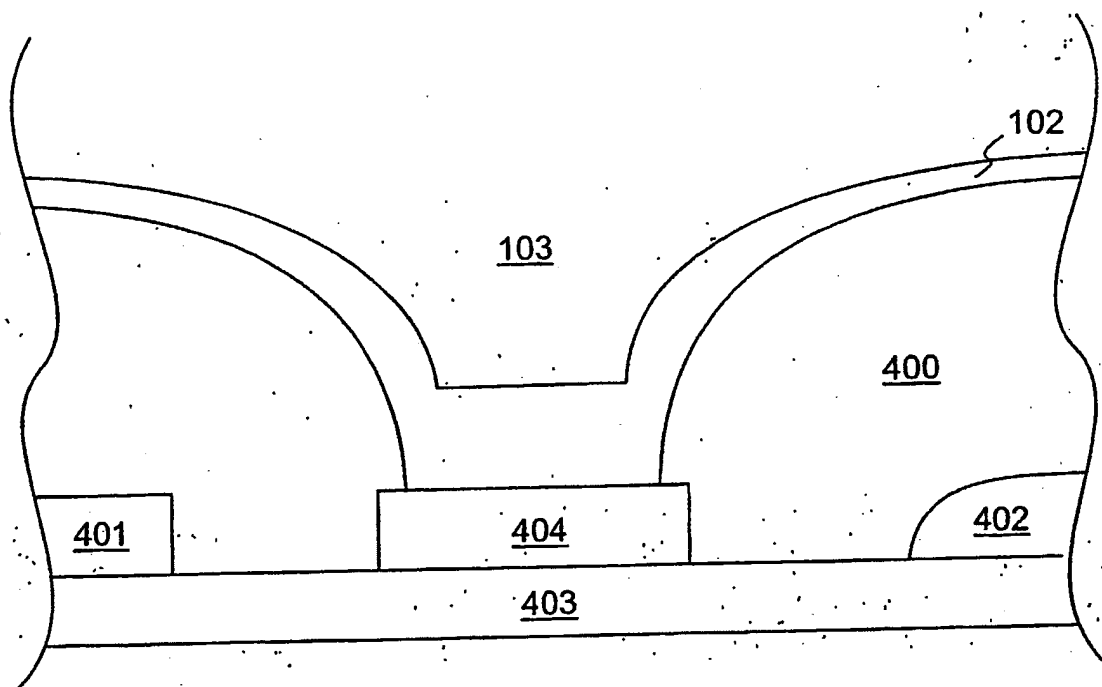
**FIG. 4B**

5/15

<u>103</u>
<u>102</u>
<u>201</u>
<u>102</u>
<u>103</u>
<u>101</u>



**FIG. 5**

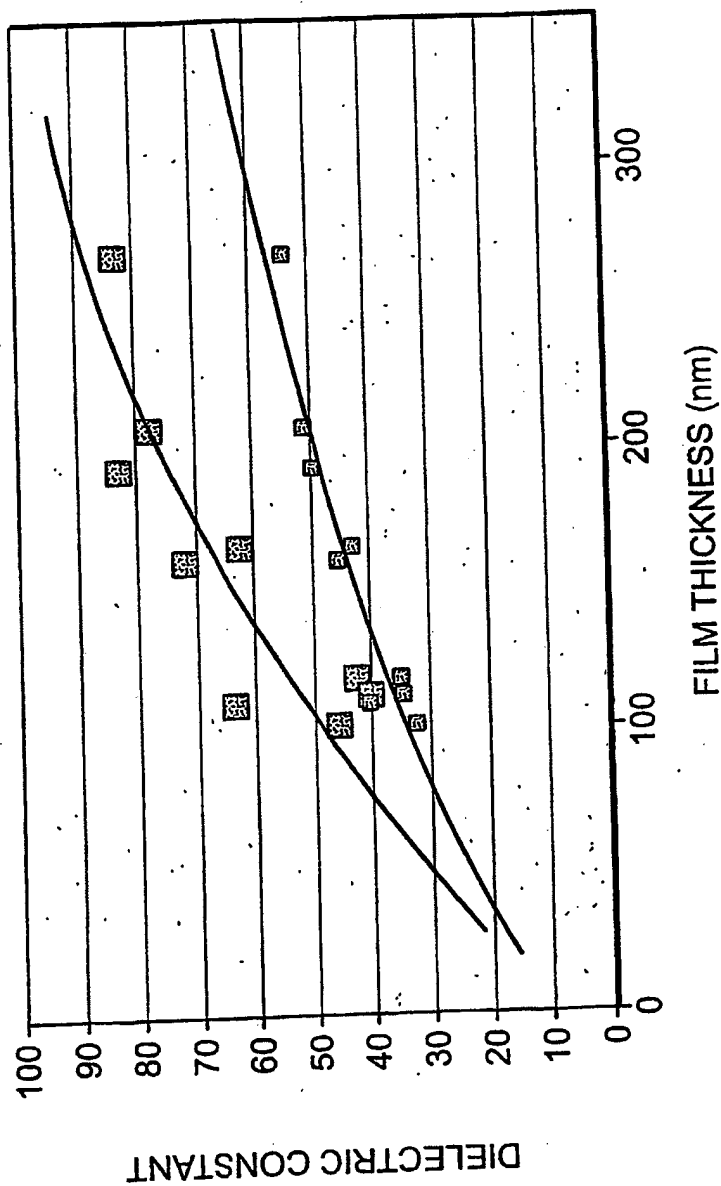
6/15



**FIG. 6**

7/15

 k (ON Al)  
 k (ON n++)



**FIG. 7**

8/15

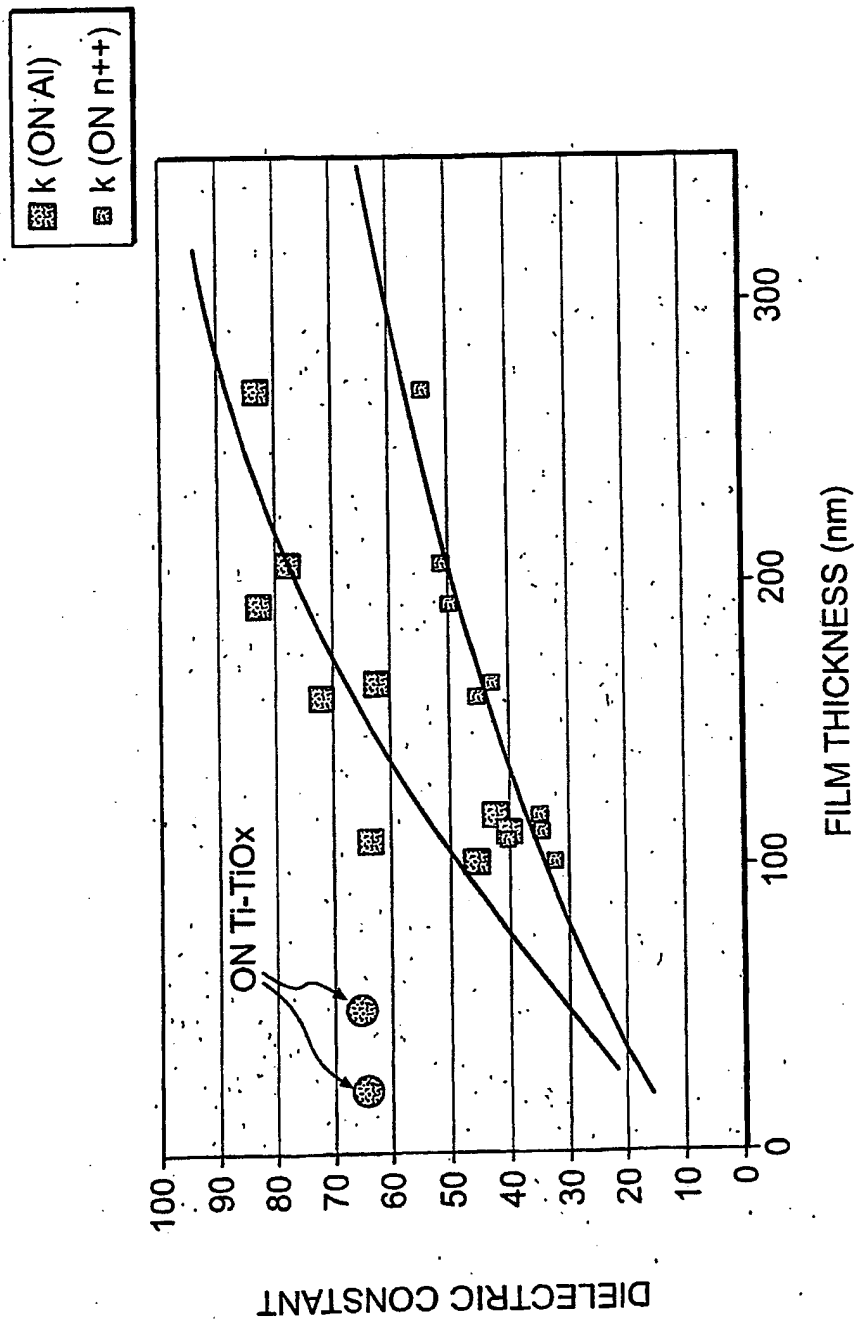
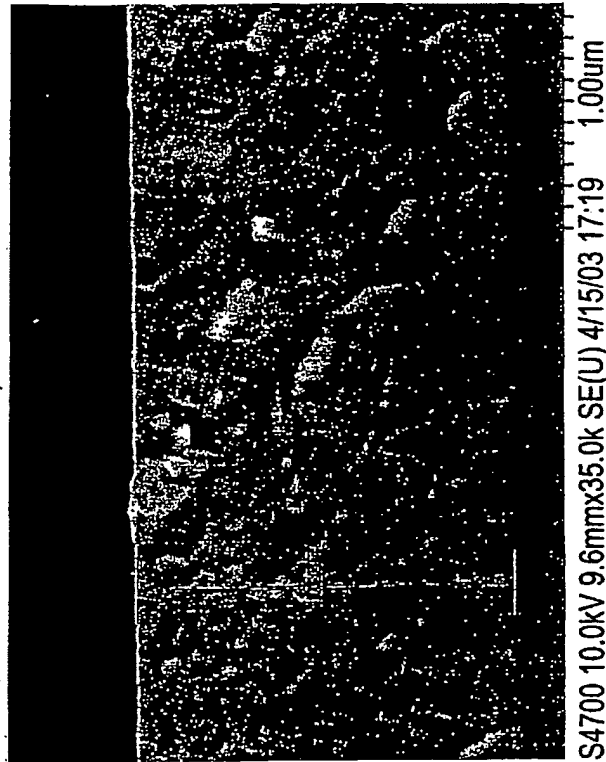
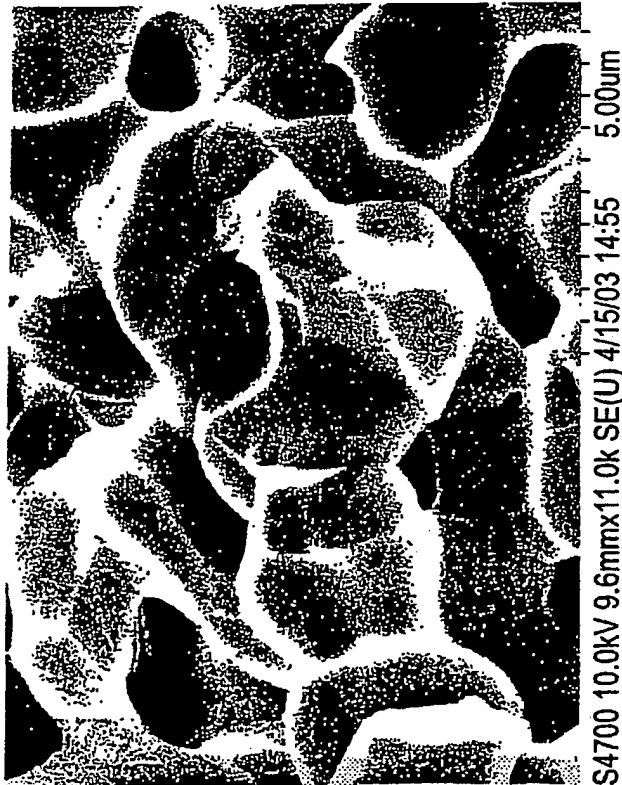


FIG. 8

9/15

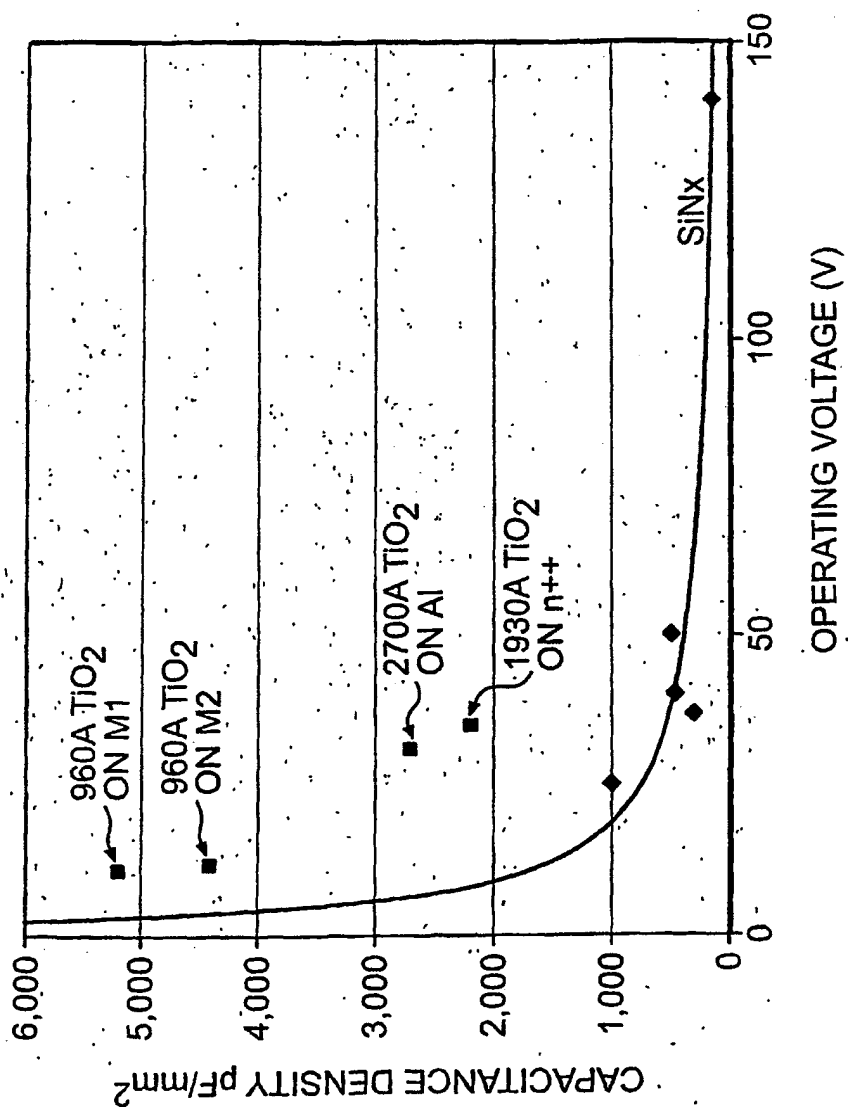


**FIG. 9B**



**FIG. 9A**

10/15



**FIG. 10**

11/15

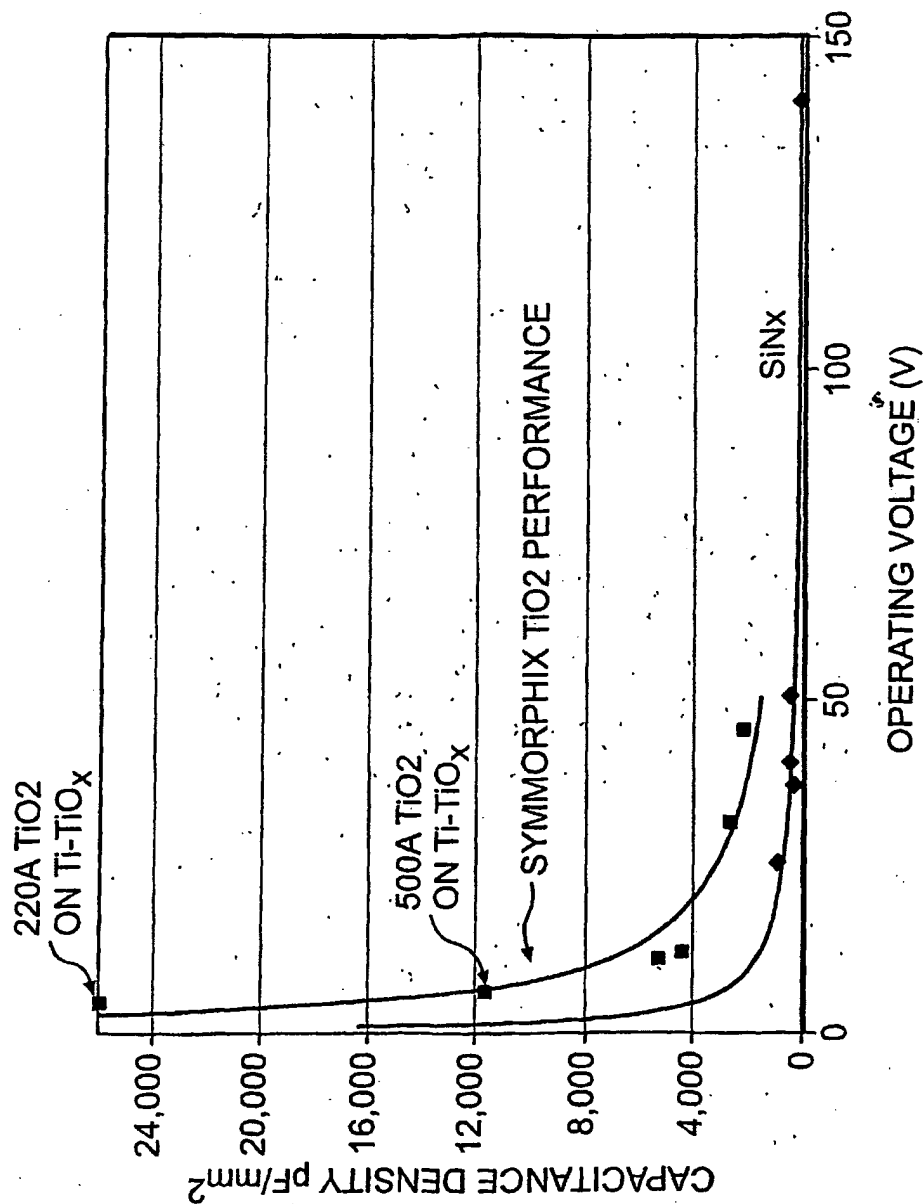


FIG. 11



12/15

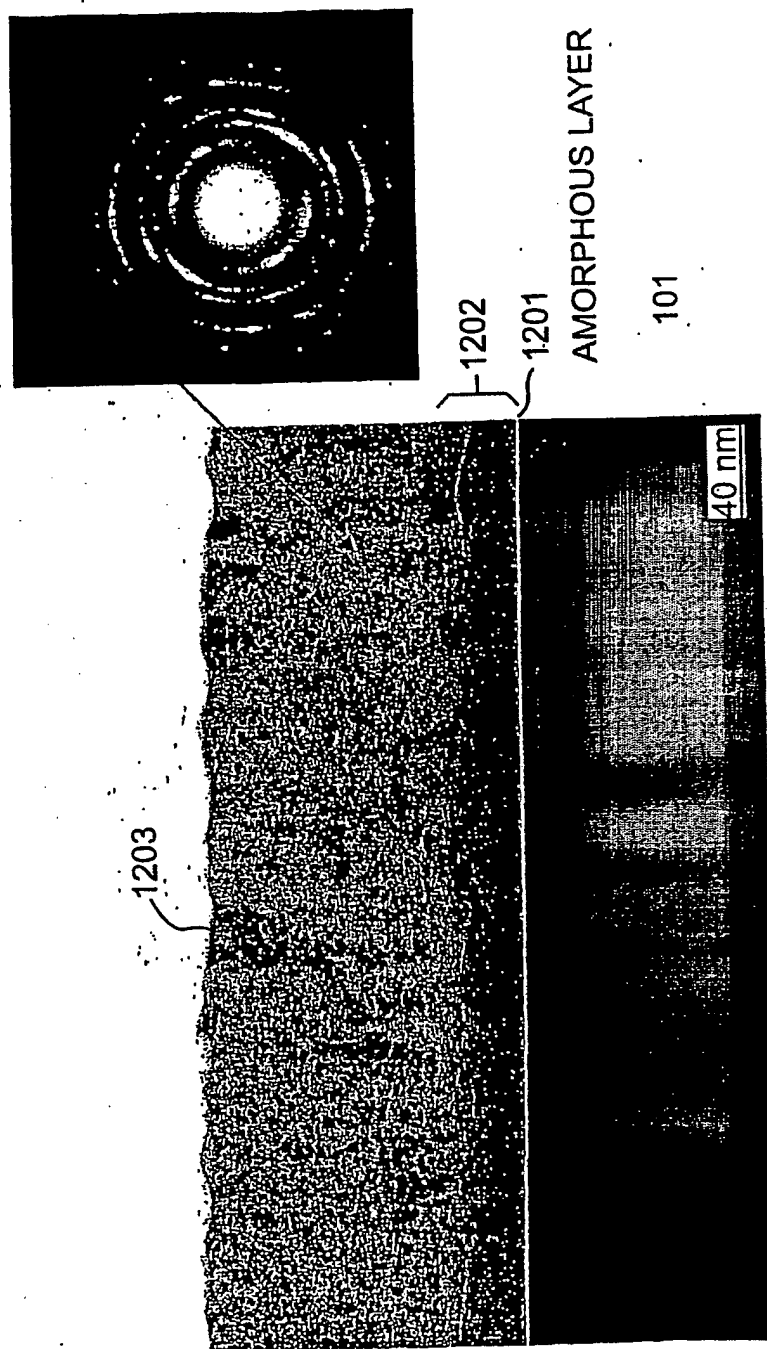
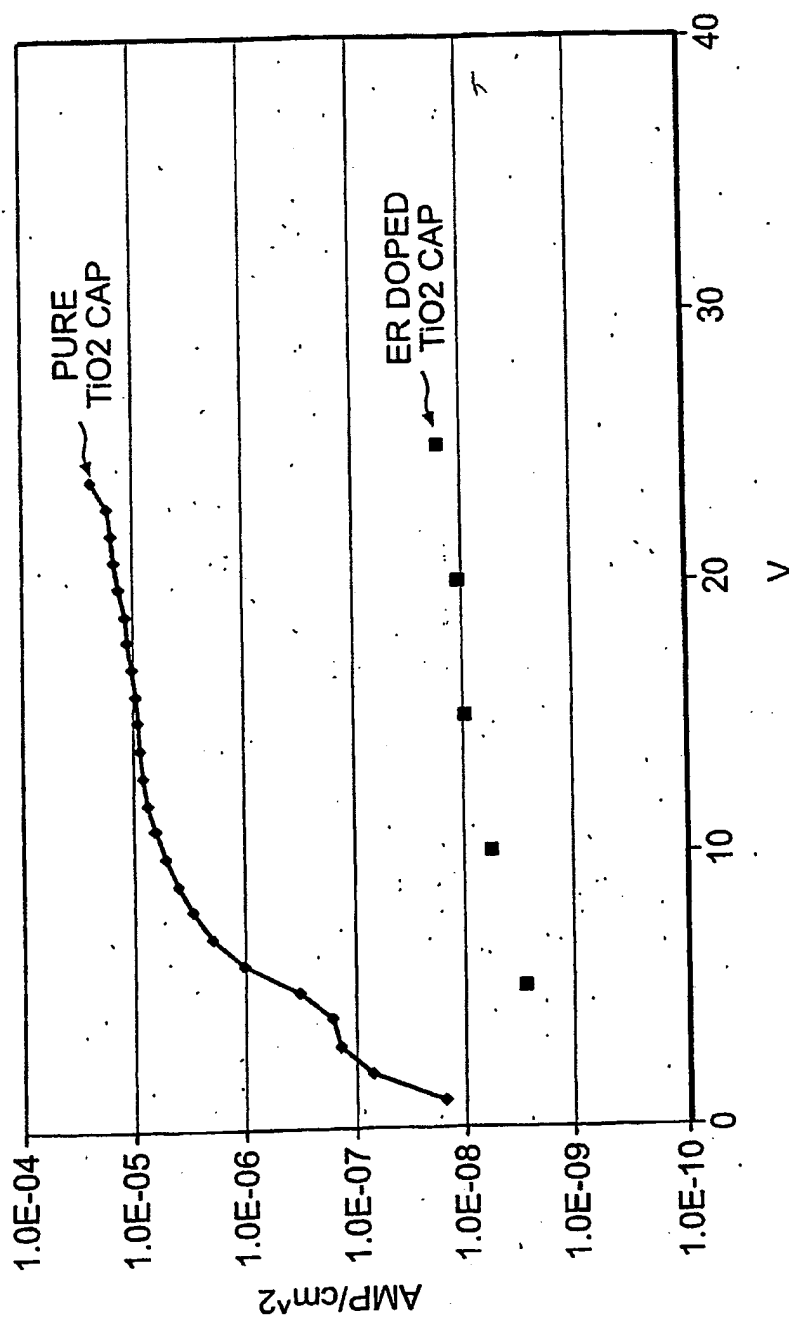


FIG. 12

13/15

**FIG. 13**

14/15

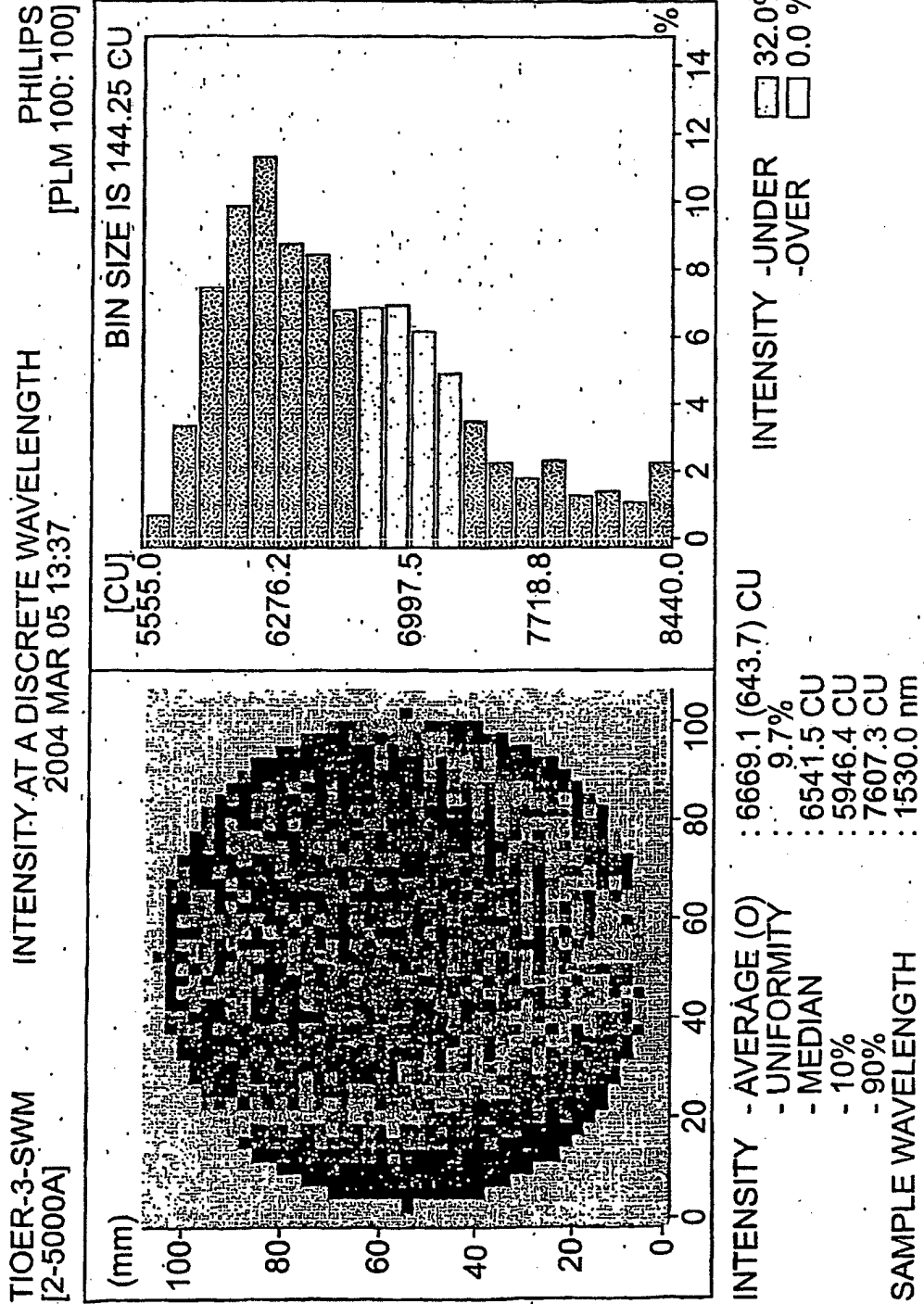


FIG. 14A

15/15

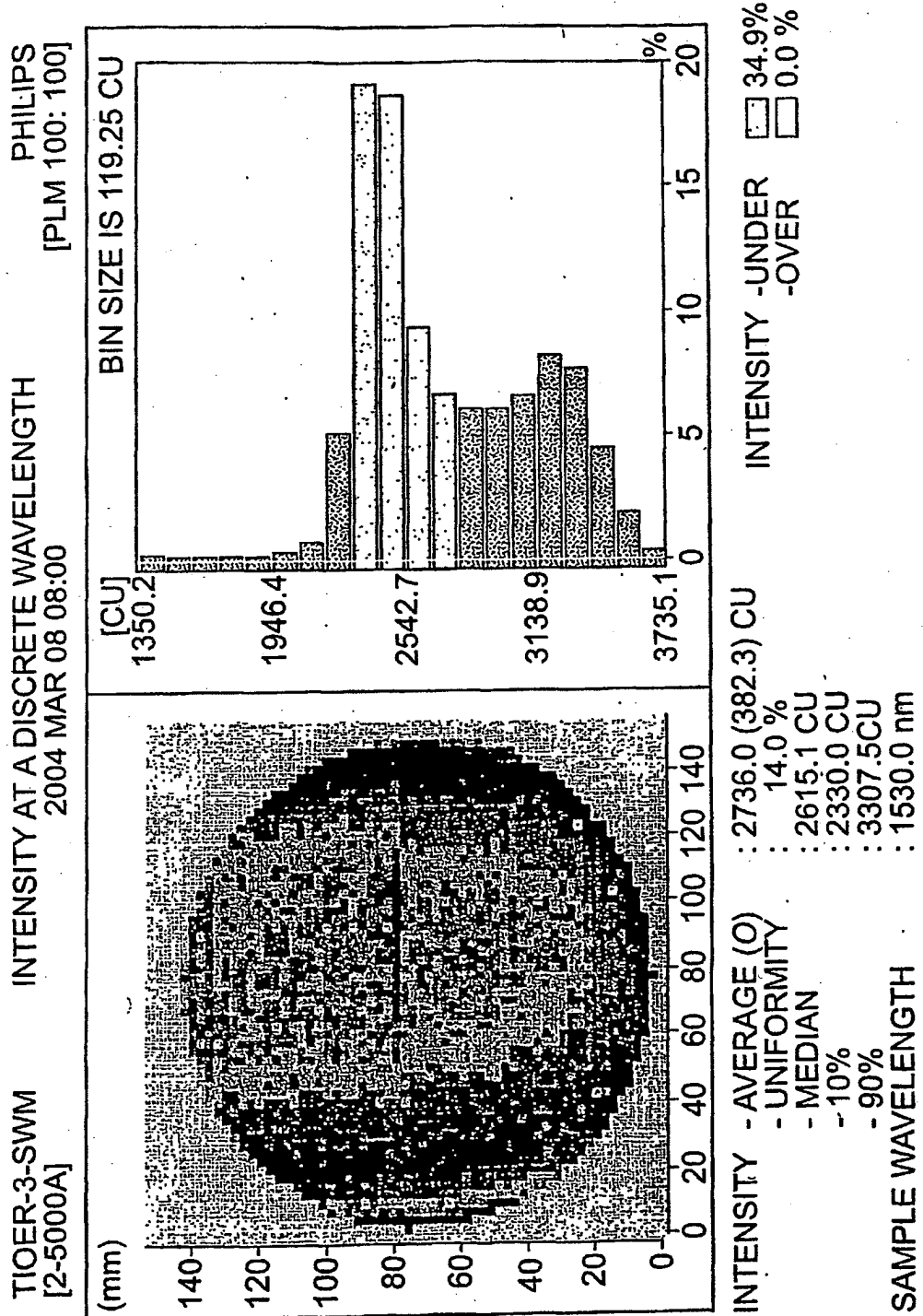


FIG. 14B

**This Page is Inserted by IFW Indexing and Scanning  
Operations and is not part of the Official Record**

**BEST AVAILABLE IMAGES**

Defective images within this document are accurate representations of the original documents submitted by the applicant.

Defects in the images include but are not limited to the items checked:

- ☐ **BLACK BORDERS**
- ☐ **IMAGE CUT OFF AT TOP, BOTTOM OR SIDES**
- ☐ **FADED TEXT OR DRAWING**
- ☐ **BLURRED OR ILLEGIBLE TEXT OR DRAWING**
- ☐ **SKEWED/SLANTED IMAGES**
- ☒ **COLOR OR BLACK AND WHITE PHOTOGRAPHS**
- ☐ **GRAY SCALE DOCUMENTS**
- ☒ **LINES OR MARKS ON ORIGINAL DOCUMENT**
- ☒ **REFERENCE(S) OR EXHIBIT(S) SUBMITTED ARE POOR QUALITY**
- ☐ **OTHER:** \_\_\_\_\_

**IMAGES ARE BEST AVAILABLE COPY.**

**As rescanning these documents will not correct the image problems checked, please do not report these problems to the IFW Image Problem Mailbox.**